Brewster effects for deep metallic gratings

L. B. Mashev, E. Popov, and Erwin G. Loewen

Total absorption of light by highly modulated metallic gratings is demonstrated both theoretically and experimentally. This phenomenon occurs when only the zeroth-order propagates and is linked with the excitation of surface plasmons.

I. Introduction

Nowadays it is well established that in certain conditions gratings may act as perfect absorbers. This phenomenon has been demonstrated both theoretically and experimentally with metallic gratings in S polarization (the electric field vector perpendicular to the grating grooves),[1,2] and for dielectric overcoated metallic gratings in P polarization (the electric field vector parallel to the grooves).[3] In the above cases the gratings are shallow, with groove depth to period ratio h/d less than 0.1 and λ/d ratio (wavelength to groove spacing) such that only the zeroth-order propagates. Although at a first glance the two cases seem to be quite different, the physical origin for the strong absorption peaks is the excitation of surface waves. We demonstrated recently that total absorption of light may occur also in the presence of two diffracted orders, in grazing incidence,[4,5] but this case is not connected directly with the excitation of surface waves.

For a shallow bare metallic grating the condition for an excitation of a surface plasmon is

$$\sin\theta - m\lambda/d = n_M/(1 + n_M)^{1/2}, \qquad m = 0, \pm 1, \pm 2 \ldots, \tag{1}$$

where θ is the angle of incidence, λ is the wavelength and n_M is the refractive index of the metal. For a plane interface Eq. (1) with $m = 0$ is nothing but the Brewster condition for complex refractive indices.

Maystre and Petit[1] have shown for the first time that there exists a value α^z of $\alpha = \sin\theta$ for which the zeroth-order efficiency of grating is zero. The value of α^z depends on the grating profile and in particular on the h/d ratio in the case of sinusoidal gratings. To quote Ref. (6): "It is worth noting that the critical groove depth h_c is generally very small. Thus it may appear unbelievable that, while a plane interface reflects more than 90% of the incident energy, a very shallow grating may absorb it in totality." The purpose of this paper is to show that such a Brewster phenomenon can be observed also for highly modulated gratings.

II. Theoretical Considerations

The calculations were performed with computer codes developed in Refs. 7 and 8, based on the rigorous formalism of Chandezon *et al.*,[9] for multicoated gratings. In the study of grating anomalies connected with surface wave excitation it proves most useful to deal with the generalization of the diffraction properties for complex values of α, for the following reasons:

(i) the propagation constant of the surface waves usually take a complex value and is directly connected with $\alpha = \sin\theta$ through the grating Eq. (1), and

(ii) this generalization enables us to find connections between different anomalies and to predict the appearance of new anomalies.

That is why the computer code was generalized to work in the complex α-plane. Poles and zeroes were found using Newton's iterative method for complex variables.

Let us consider a sinusoidal aluminum grating with d = 0.5 μm, illuminated by an S-polarized plane wave with $\lambda = 0.6328\,\mu$m. The efficiency of the zeroth-order as a function of h/d ratio is shown in Fig. 1.

The main feature of the curve in Fig. 1 is the discovery of three minima for values of h/d up to 1.4. The angle of incidence corresponds to a real zeroth-order zero for $h/d = 0.8$. By slightly modifying α, the values of h/d for which the other two minima are zeroes can also be obtained.

At low h/d ratios the first absorption peak in Fig. 1 corresponds to the Brewster effect, described in Refs. 1 and 2. Obviously, such a phenomenon is characteristic not only for shallow gratings, but also occurs for

Erwin Loewen is with Milton Roy Company, Analytical Products Division, 820 Linden Avenue, Rochester, New York 14625; the other authors are with Bulgarian Academy of Sciences, Institute of Solid State Physics, 72 Lenin Boulevard, Sofia 1874, Bulgaria.

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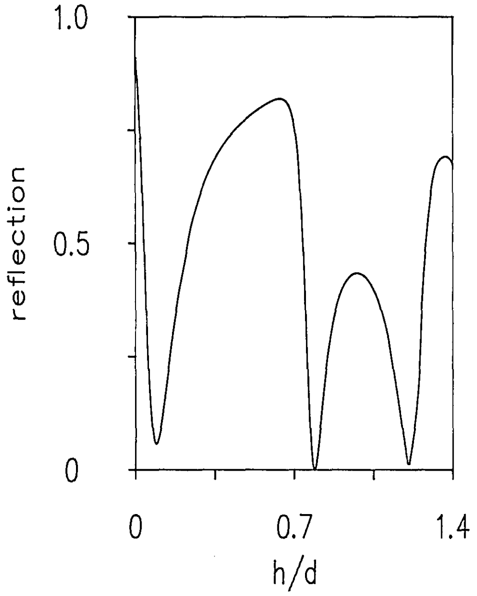

Fig. 1. Groove depth dependence of the reflection of a sinusoidal aluminum grating ($n_M = 1.378 + i7.616$) for $\alpha = 0.25762$.

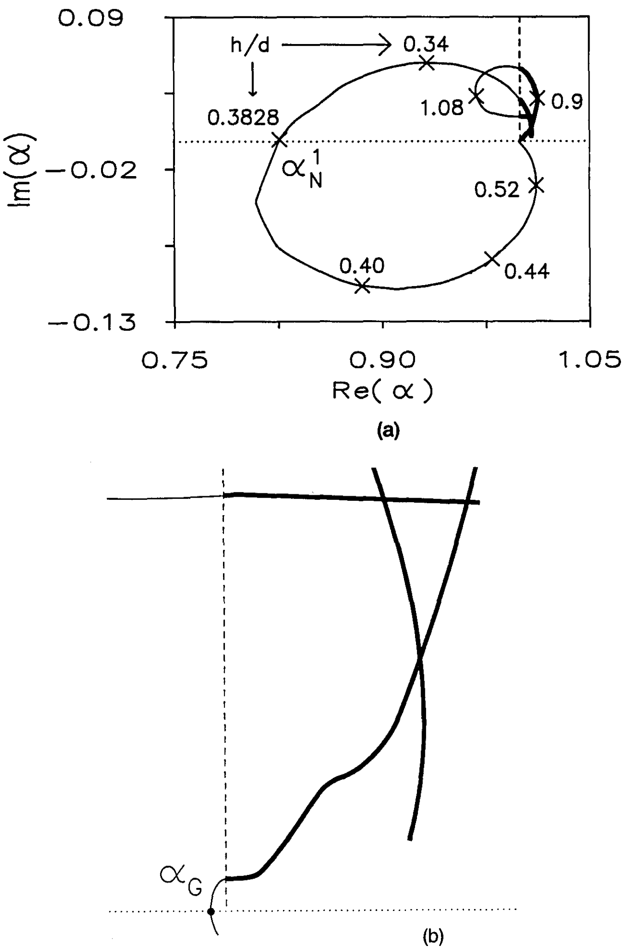

Fig. 2. (a) Trajectory of the pole (heavy solid line) and the zero (solid line) of the zeroth-diffraction order in the complex α-plane for different h/d values. The cut is denoted by a dashed line and the real α-axis by a dotted line. (b) 15× magnification in the vicinity of the point (1.0).

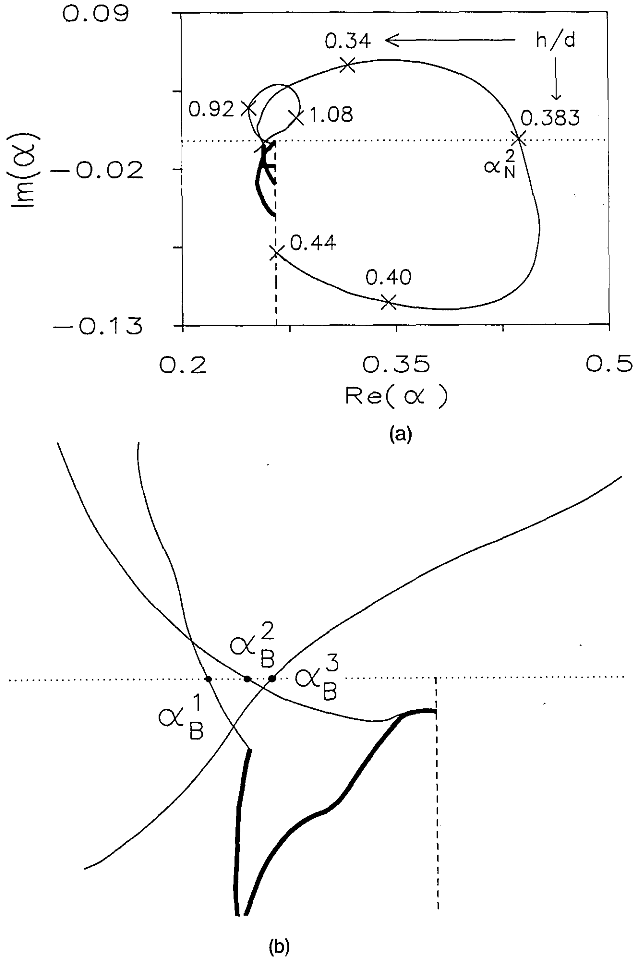

Fig. 3. (a) and (b). The same as in Fig. 2, except for the vicinity of the second cut $\alpha = 1 - \lambda/d$.

deep gratings. The second minimum appears at $h/d = 0.8$, and the third one at $h/d = 1.2$. Since at these conditions no diffraction orders other than the zeroth are allowed, the existence of a real zero of the zeroth-order efficiency means that the incidence energy is absorbed totally by the grating.

The link of the Brewster phenomenon with other types of grating anomalies can be established by numerical tracing of the poles and the zeroes of the scattering matrix of the system in the complex α-plane (Figs. 2 and 3). A detailed description of these figures will be published later; here we shall point out only the main features which are connected with total absorption of light.

Figure 2 represents the trajectory of the pole and the zero of the zeroth-order for complex values of α as a function of the modulation depth h/d up to 1.35. For small h/d ratios (<0.2) the pole α^p is connected with surface plasmon excitation. As h/d increases α^p crosses the cut and is transferred into a zero which has two cross-points with the real α-axis. The first one, denoted by $\alpha_N{}^1$ corresponds to the non-Littrow perfect blazing[10,11] for finitely conducting gratings. The second cross-point denoted by α_G appears near grazing incidence and is responsible for the anomaly, described recently by us.[4,5] Increasing the modulation depth further, the zero crossing the cut is transferred again into a pole and then a second loop in the trajectory is formed.

The pole trace in Fig. 3 corresponds to surface plasmon excitation, carried out through the -1st-order and is symmetrical to the curve in Fig. 2 with respect to Littrow mount. In this case the pole is accompanied by a zero (see, for example, Ref. 12), and for perfectly conducting gratings the trajectories of the pole and the zero are symmetrical with respect to the real α-axis due to the unity of the scattering matrix. The trajectory of the zero in the complex α-plane crosses the real α-axis at four points:

(i)—at $h/d = 0.1$. The first zero $\alpha_B{}^1$ corresponds to the Brewster phenomenon in shallow metallic gratings[1,2] and is responsible for a total absorption of light by a grating.

(ii)—for $h/d = 0.38$ the zero $\alpha_N{}^2$ is symmetrical to $\alpha_N{}^1$ with respect to Littrow mount and represent a second non-Littrow perfect blazing for real metal gratings. With increasing h the zero trace disappears crossing the cut. This fact has a simple explanation at least for perfectly conducting gratings: on the other side of the cut only the zeroth-order propagates and therefore the zero cannot exist because of the energy balance criterion. The zero appears again on the cut at $h/d \approx 0.72$ accompanied by a pole.

(iii)—for $h/d = 0.8$ and

(iv)—for $h/d = 1.2$, the real zeroes $\alpha_B{}^2$ and $\alpha_B{}^3$ correspond to the second and third Brewster phenomenon shown in Fig. 1 for deep metallic gratings. Although the position of the three zeroes almost coincide, their location is strongly influenced by the metal refractive index (Fig. 4).

For perfectly conducting gratings the real zero $\alpha_B{}^2$ is exactly symmetrical to the grazing zero α_G with respect to Littrow mount and crosses the real α-axis in the region where two-orders are propagating (Fig. 4). Thus, there is no contradiction with the energy balance criterion. Reducing the imaginary part of the refractive index, $\alpha_B{}^2$ is moved towards the -1st-order threshold angle. At $Im(n_M) \approx 15$ the zeroth-order zero appears in the region where -1st-order is below the cutoff thus a total light absorption is observed.

In addition, the presence of a thin oxide layer on the aluminum surface, typically few nanometers thick,[13] also changes the position of the absorption peak (Fig. 5). Further on, the results refer to gratings, coated with aluminum ($n_M = 1.09 + i5.31$) with an oxide layer 2.5 nm thick. These values provide quite accurate results not only for the shape and the location of the resonance anomalies, but also for the polarization characteristics of gratings in conical diffraction mounting.[14]

III. Experimental Confirmation

A grating with a period $d \approx 0.5$ μm was recorded interferometrically in a photoresist Shipley AZ-1350 with Argon ion laser beams with spherical wavefronts originating from two pin-holes acting as point sources. The laser fields conical diameter in the plane of interference was a little bit larger than the blank. After development the grating was coated with 200-nm thick layer of aluminum. The grating is highly nonuniform with respect to the groove depth. However, the exposure—development process was chosen such as to provide a grating profile close to sinusoidal.[15]

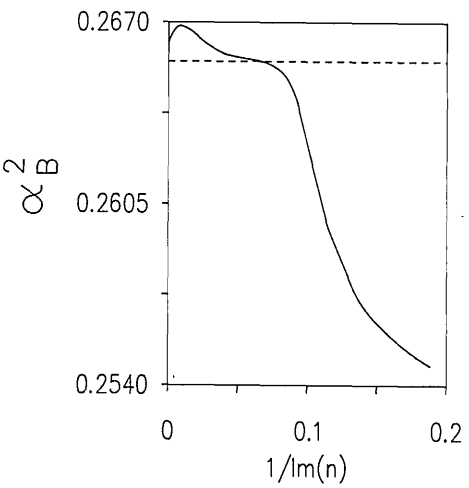

Fig. 4. Location of the second Brewster zero of the zeroth-order as a function of the imaginary part of the metal refractive index. The -1st-order cutoff is shown with a dashed line.

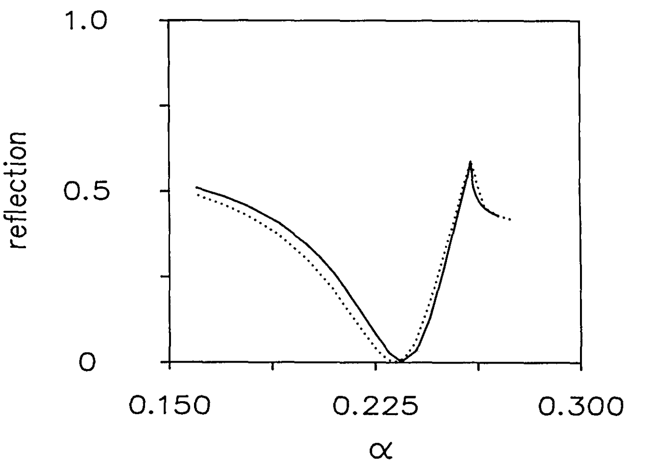

Fig. 5. Influence of an oxide layer on the aluminum surface ($n_M = 1.09 + i5.31$) on the position of the absorption peak. Solid line—bare grating, dotted curve—aluminum grating coated with 2.5 nm thick dielectric layer with a refractive index 1.538.

The modulation depth was reconstructed from comparison between the measured efficiency as a function of the distance from the center, with the theoretical efficiency, as a function of h/d, for both S and P polarizations at 3° angular deviation from Littrow mount. The good agreement between two sets of curves allowed us to estimate the groove depth at each point of the grating and confirmed that the maximum achieved modulation depth was about 0.9.

Since the recording was performed by two spherical waves, the period of the grating was not constant. Therefore, for each point of the grating the period was measured, too. The efficiency of the zeroth-order was measured as a function of the angle of incidence with

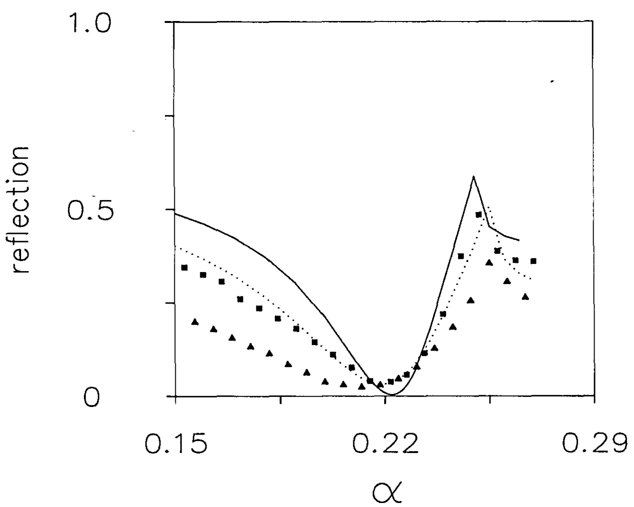

Fig. 6. Reflection as a function of $\alpha = \sin\theta$ for $h/d = 0.8$ (solid curve—theoretical results, squares—experimental results) and for $h/d = 0.85$ (dotted curve—theoretical results, triangles—experimental results).

the beam of S-polarized He-Ne laser falling onto two points of the grating, where the modulation ratios $h/d = 0.8$ and $h/d = 0.85$, respectively. The results, together with the calculated ones under the same conditions, are given in Fig. 6. Good agreement between the theoretical and the experimental results is observed, especially with respect to the position of the absorption peaks.

The relatively broader half-width of the experimental anomalies can be explained, by taking into account that:

(i) the actual intensity distribution of the incident wave is Gaussian,

(ii) the grating is not uniform in depth, therefore the laser spot covers regions with varying h/d, and

(iii) very deep gratings have a quite noticeable transmission; thus, it is not quite correct to consider them as bare aluminum gratings.

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